

GALAXY ASSOCIATIONS WITHIN THE COMA CLUSTER

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Abstract

The mean redshift of the core of the Coma cluster - $cz = 6953 \text{ km s}^{-1}$ and its dispersion $\sigma = 949 \text{ km s}^{-1}$ are obtained by means of the analysis of the substructures of this cluster by using the S-tree method. The existence of three subgroups of galaxies is revealed, one of them is associated with the cD galaxy NGC 4874, the other – with NGC 4889. It is argued that these subgroups are *galaxy associations*, i.e. galactic dynamical entities moving within the main cluster. Thus we conclude that the non-stationarity of the dynamical processes ongoing in the Coma core is due to the merging of small-scale galaxy associations, rather than of two equal sized clusters. We provide the lists of the galaxies of the associations, the observational study of which can be of particular interest.

PACS: 98.62L

Keywords: Galaxies - Clusters.

1 Introduction

In (Gurzadyan & Mazure, 1998) we have studied the substructure of several Abell clusters from the ESO Key Program ENACS database (Mazure et al 1996). The analysis was carried on using the S-tree method (Gurzadyan et al 1994). It was shown that the studied clusters contain 2-3 subgroups, denoted, due to their remarkable dynamical properties, as *galaxy associations*. Those dynamical properties include the truncated 1D velocity distribution and relatively stable velocity dispersion. It was argued that the motion within the main cluster can be the natural mechanism explaining such a truncation. Because of the essential role that galaxy associations can have for the understanding of the evolution of galaxy clusters, their further study

seems of particular importance. This concerns especially observational studies, since the galaxies of the associations have to exhibit anomaly strong star formation activity, anomalies of a disk and bulge for spirals, possible tidal tails, etc, with more probability that ordinary galaxies of the cluster.

Here we analyze the core substructure of the Coma cluster using the S-tree method. The Coma cluster is one of the most studied clusters with remarkable substructure (e.g. Rood & Sastry, 1971; Valtonen & Byrd, 1979; Baier 1984; Mellier et al 1988; Dressler & Shechtman 1988; Escalera et al 1992; Fabian et al 1994; Gambera et al 1997; Kashikawa et al 1998); for more references see (Mazure, et al 1998). The internal dynamics and the substructure of Coma have been extensively analyzed by Biviano et al (1996); Colless & Dunn, (1996). Though the main conclusions of both studies are in agreement, there are some differences concerning the structure of the central region of the cluster. In general, the main tools in such investigations, on one hand, involve various statistical methods, the wavelets being among the efficient ones, and creation of various models based on certain assumptions on the cluster's symmetry, equilibrium, dark matter distribution, etc. (e.g. Merrit 1987), on the other hand.

The X-ray observations of the Coma cluster, especially by ROSAT (White et al 1993; Vikhlinin et al 1997), add crucial information on the substructures, as well as on the processes governing the mechanisms of X-ray emission. Both the galactic data and the X-ray images of Coma support the existence of substructures in the cluster, and the problem comes to the clear identification of the basic dynamical mechanisms responsible for the evolution of the cluster. Clearly, the further combination of data on the galaxies and X-ray data will enable much deeper insight onto the structure of the cluster, though one has to better understand the dynamics within the cluster, in order to proceed from realistic assumptions on the equilibrium conditions on the X-ray emitting gas.

Our study of the Coma core reveals the existence of 3 subgroups, which appear to be galaxy associations. Two of the latter are associated with the brightest cD galaxies NGC 4874 and NGC 4889, respectively. Their dynamical parameters are established, which enables us to conclude that they are moving within the cluster, so that one is a young merger, while the subgroup of NGC 4889 has been already largely dissolved. The segregation of galaxies within the subgroup we incline to explain not by core-halo evolution, but via dynamical friction during the motion. The obtained results indicate this essentially non-stationary character of structure of Coma cluster, and do not support the view that the latter can be a result of merging of two clusters

of equal size.

2 Data

In the analysis below we have used the data compiled by Biviano et al (1996); their dataset of galaxy redshifts is based on their own observations with CFHT, on the data by Colless and Dunn (1996) and those available in the literature. The authors provide also the completeness data with respect to the limiting magnitude. From this dataset we have extracted a sample of 188 galaxies in a $3000'' \times 3000''$ field centered on $\alpha = 12^h 57^m .3$, $\delta = 28^\circ 14' .4$ and brighter than $18^m .0$ (Mazure and Gurzadyan 1998). This choice was determined by data completeness with respect to magnitude.

3 Method

The S-tree technique developed for the study of the hierarchical substructure of galaxy clusters is described in detail in (Gurzadyan et al 1994; Gurzadyan & Kocharyan 1994). It is based on the methods of theory of dynamical systems and has already been used for the study of substructure of the various clusters of galaxies, including the Local Group, Virgo (Petrosian et al 1998) and the sample of above mentioned ENACS Abell clusters.

This method is using the information on the 2D coordinates, redshifts and magnitudes of galaxies in a self-consistent way, namely, revealing the correlation which should exist between the particles' parameters (coordinates and velocities) of a gravitationally interacting N-body system. It is reached using a well know method in classical mechanics reduced to the study of the properties of the flow of geodesics in phase space of the system (Arnold, 1989). Namely the so-called two-dimensional curvature

$$K_{\mu\nu} = Riem_{\rho\delta\mu\nu} u^\rho u^\delta$$

(*Riem* is the Riemannian tensor, *u* is the velocity of geodesics) is used for the evaluation of the 'degree of boundness'; for details see (Gurzadyan & Kocharyan 1994) and the Appendix in (Gurzadyan & Mazure, 1998). This procedure enables to reveal the structure of the system including the existence of subgroups and representation of the result via tree-diagrams (S-tree). In the above quoted papers the role of the magnitude completeness, M/L ratio of galaxies and other effects are discussed as well. Special algo-

rithms are used also for the analysis of the outcome information (Bekarian & Melkonian 1997).

4 Substructure of the Coma Core

This is not the first cluster studied via the S-tree method, therefore we will not repeat the description of the technical steps of the analysis. Thus, our analysis revealed the substructure of the core of Coma cluster, namely, the complex structural and dynamical conditions in the core of Coma cluster. First, the code has enabled to extract the galaxies with correlated parameters, thus defining the main physical system (MS) of galaxies: it contains 174 galaxies, centered at $\alpha = 12^h57^m32^s.3$, $\delta = 28^\circ19'31''$. The knowledge of the membership of galaxies is readily defining the redshift of the Coma cluster and velocity dispersion: $cz = 6953 \text{ km s}^{-1}$ and $\sigma = 949 \text{ km s}^{-1}$, respectively.

Then, at higher level of correlation, i.e degree of the mutual boundness, the existence of 3 subgroups of MS has been revealed. The subgroups contain 34 galaxies (1s), 14 galaxies (2s) and 17 galaxies (3s), as exhibited in Tables 1-3.

The 1st subgroup includes the 2nd brightest galaxy of the Coma core - NGC 4874. The center of this subgroup lies at $\alpha = 12^h57^m34^s.31$, $\delta = 28^\circ15'35''.45$, i.e. does not coincide with NGC 4874.

The obtained parameters of galaxies of the MS and the subgroups are presented in Table 4, which includes the number of galaxies (N), the median velocity (m, in km s^{-1}), standard deviation of the redshift distribution (σ , in km s^{-1}), 3rd and 4th moment of the redshift distribution, (s) and (c), respectively. We do not include any estimation of the error box for the standard deviation, since its precise value is not only of minor importance for our main aim of the subgrouping, but also due to the inhomogeneity of the input data, any weighting, strictly speaking, will add a bias in such estimation.

Figure 1 shows the histograms of the redshift distributions of the initial sample, the MS, and of the three subgroups.

5 Discussion

The results obtained above enable us to draw the following picture on the substructure and the dynamical processes evolving in the Coma core.

We have identified the galaxies forming the main body of the Coma cluster and have obtained its redshift and the velocity dispersion: $cz = 6953 \text{ km s}^{-1}$ and $\sigma = 949 \text{ km s}^{-1}$, respectively. These parameters do not differ much from those obtained before (Biviano et al, 1996, Colless & Dunn 1996), except the center of the cluster does not coincide exactly with the dominant galaxy NGC 4874, though lies in its vicinity.

Then, we have revealed 3 subgroups of galaxies within the main system and have determined the characteristics of each of them, given in Table 4. Careful look of those parameters enables to understand certain dynamical processes going on within the cluster. Namely, the clear separation of the subgroups in the redshift space indicates their essential mutual bulk motion (Gurzadyan & Mazure 1998), i.e. when the bulk velocity is exceeding the velocity dispersion of each subgroup. This can mean ongoing merging of the subgroups, as confirmed below by additional arguments. The 3rd and 4th momentum show the absence of asymmetry on one hand, and stronger truncation of subgroups' (as compared with the main system) redshift distribution, on the other hand. Truncation of the subgroups, i.e. the cutoff of the the velocity dispersion of galaxies in the subgroups must occur at the motion of the subgroups within the main system (Gurzadyan and Mazure 1998).

Further evidences support this conclusion. NGC 4874 ($\alpha = 12^h 57^m 27^s .38$, $\delta = 28^\circ 13' 43''$, $cz = 7176 \text{ km s}^{-1}$) is not situated at the mass center of subgroup 1 and its redshift does not coincide with the median redshift of the subgroup containing the several bright galaxies of the Coma cluster, i.e. 5 galaxies brighter 15^m (see Table 2). Such a redistribution of galaxies is inevitable due to dynamical friction, if the group of galaxies is moving through a galaxy field.

Biviano et al (1996) proposed to explain the overdensity of bright galaxies in the vicinity of NGC 4874 by the core-halo segregation mechanism during the own evolution of the subgroup. However, this mechanism is efficient in isolated stellar systems with large number of stars, while at least the required virialization is never reachable for a small-number galaxy group moving within a giant host system. The dynamical friction, on the other hand, does not depend on the smallness of the number of galaxies since acts on each galaxy individually, depending on the mass and the velocity of the moving object, and hence can be responsible for the observed segregation; for the observed galaxy/subgroup parameters the efficiency of dynamical friction requires time scales $10^8 - 10^{10}$ yrs, i.e. cosmologically quite reasonable scale. This is again supporting the significance of the regular motion of

the subgroup within the host cluster. Subgroup 1 shows better separation by 'degree of boundness' from the galaxies of the main cluster in redshift space, while the galaxies of subgroup 3 are more overlapped with redshifts of main cluster, i.e. there are galaxies not belonging to subgroup 3, but having redshifts lying within the redshift interval of that subgroup. Since one can hardly accept the possibility of the formation of the dynamical subgroups during the evolution of the main cluster and hence doubt in their primary origin and in their further dissolution within the cluster, the above fact can indicate only the more stronger dissolution of subgroup 3, as compared with the subgroup 2. In other words the former has to be an elder merger; this conclusion is supported also with the essential shift of the velocity of NGC 4889 ($\alpha = 12^h56^m55^s$, $\delta = 28^\circ14'46''$, $cz = 6497 \text{ km s}^{-1}$) from the median velocity of subgroup 3, a result of an action of dynamical friction. Similar conclusion has been drawn by Colless and Dunn (1996) from other considerations.

Thus, the present study indicates the existence of subgroups - galaxy associations - in Coma cluster which are undergoing the merging process, since essential bulk velocities and dissolution must mean only merging and not any time-reversed processed. It is remarkable that the subgroups are in various phases of merging. Indeed, the truncation of redshift distribution for the elder merger (subgroup 3) is more evident than for subgroup 1, so that only a core of galaxies had survived in the subgroup 3. Essential bulk velocity has been revealed also for the subgroups of the Local group (Gurzadyan & Rauzy, 1997; Rauzy & Gurzadyan, 1998).

The existence of merging subgroups with mutual bulk motion within the host cluster does not support the idea that the Coma cluster is a result of merging of two equal sized clusters (e.g. Tribble 1993) but is in agreement with one of the alternatives mentioned already by Fitchett and Webster (1987).

The fact that essentially non-stationary dynamical processes are ongoing in the core of Coma cluster affects the interpretation of the X-ray data as a way to reveal the structure of the cluster; see (Mazure et al 1998; Kikuchi et al 2000) for references. Particularly, the isothermal assumption on the X-ray gas state leads to an overestimation of the mass of the system within the given radius. A multi-temperature gas will mean that the X-ray flux peaks will depend on the wavelength, and therefore the correlation of the X-ray peaks with galaxy distributions may be not straightforward (cf. Biviano et al 1996) .

The available data on the galaxies of the subgroups given in the Tables

1-3 show some peculiarities. For example, the subgroup 3 is almost totally composed of S0 galaxies. Seems remarkable also the non-random orientation of the galaxies in subgroup 1 (Fig. 2).

Another observational aspect concerns the individual properties of the galaxies of the subgroups. It is now becoming clear that even minor external perturbations can be the reason of various galactic anomalies, such as the starburst activity (Bekki 1999), disk thickening of spirals (e.g. Reshetnikov and Combes 1997), bar formation and misalignment (Curir and Mazzei 1999, Chitre et al 1999), low metalicity globular cluster formation (Tanighuci et al 1999, Smith 1999), tidal tails and bridges (Conselice and Gallagher 1998), counter rotating disks, etc. The galaxies of subgroups with essential bulk velocity have to undergo more perturbations and hence to reveal more of those properties than the galaxies of the field. Hence the observational study of the galaxies listed in Table 1-3 can be of particular interest, since the above mentioned tidally triggered phenomena link the dynamically detected galaxies with their individual properties.

We are thankful to F.Combes and G.Comte for valuable discussions. V.G. was supported by French-Armenian Jumelage.

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Table 1: Subgroup 1. The columns indicate: Col 1 GMP No, Col 2 Velocity from Biviano et al (1996), Col 3 and 4 X, Y in arsec from GMP, Col 5 B mag from GMP, Col 6 R mag from GMP, Col 7 B-R from GMP, Col 8 Ellipticity from GMP, Col 9 Orientation from GMP, col 10 V mag from GMP and GP, Col 11 Morphological type from Biviano et al compilation: (Morphological type from Dressler(1980), or from M88 (2nd choice), numerically coded as follows: E=1.0, S0=2.0, Sa=3.0, Sb=4.0, generic SP=5.0, Sc=6.0, Sd=7.0, Sm=8.0, I=9.0. Intermediate or uncertain cases, such as "E/S0" or "S/I" have a number intermediate between the two classes, e.g. E/S0=1.5, S/I=8.5. Barred galaxies have their number incremented by 0.1, e.g. S0B=2.1, SBb=4.1. Peculiar galaxies have their number incremented by 0.2, e.g. Sp=5.2, S0p=2.2). Col 12: Spectrum classification, according to C93: 0=normal; 1=abnormal, with some doubts; 2=abnormal. Col 13: Galaxy number in IC/NGC catalogues.

GMP	VEL	X	Y	B	R	B-R	Ell	The	V	Type	Class	Ident
2615	6707	-627	-736	16.97	0.00	1.90	0.3	98	15.70	2.5	0	
2535	7056	-736	94	15.93	0.00	1.90	0.3	49	14.75	2.0	0	IC4041
2654	6984	-565	-52	16.38	0.00	1.90	0.3	13	15.21	2.0	0	
2798	6811	-429	-54	14.85	0.00	0.00	0.0	0	13.82	1.0	0	NGC4898A
2866	6992	-363	-680	16.90	0.00	1.79	0.2	18	15.73	1.0	0	
2912	6756	-316	719	16.07	0.00	1.80	0.4	96	14.93	1.0	0	
2922	7196	-303	388	15.93	0.00	1.86	0.1	149	14.75	1.0	0	IC4012
2940	7245	-280	120	16.08	0.00	1.82	0.1	149	15.24	1.0	0	IC4011
2943	7249	-279	1008	17.66	16.39	0.00	0.3	163	16.73	0.0	0	
3017	6784	-209	-91	17.91	16.28	1.65	0.2	104	17.08	1.0	0	
3055	6691	-168	994	14.73	0.00	1.87	0.1	152	13.60	1.0	0	NGC4881
3129	6729	-69	626	17.94	16.26	1.71	0.5	173	16.78	0.0	0	
3201	6629	10	-210	15.51	0.00	1.91	0.0	0	14.46	1.0	0	NGC4876
3206	6892	14	-43	16.36	0.00	1.79	0.4	18	15.81	2.0	0	
3213	6841	19	87	16.14	0.00	1.83	0.1	131	15.21	1.0	0	
3222	6946	38	-166	16.47	0.00	1.75	0.1	162	15.53	1.0	0	
3238	6722	53	-1119	16.75	0.00	1.88	0.2	124	15.55	4.0	0	
3291	6812	92	61	16.41	0.00	1.78	0.3	45	15.73	2.0	0	
3329	7176	124	-41	12.78	0.00	0.00	0.0	0	12.20	1.0	0	NGC4874
3352	7205	147	-86	14.79	0.00	1.78	0.0	0	14.29	1.5	0	NGC4872
3390	6832	183	275	15.89	0.00	1.75	0.3	120	14.33	2.0	0	
3414	6717	202	-52	14.89	0.00	1.90	0.4	173	14.19	2.0	0	NGC4871
3423	6817	211	-434	15.80	0.00	1.95	0.5	154	14.65	2.0	0	IC3976
3471	6665	247	101	16.45	0.00	0.00	0.2	148	15.76	1.5	0	
3510	6992	289	-214	14.97	0.00	2.06	0.1	173	13.85	1.0	0	NGC4869
3554	7125	332	374	17.20	15.33	1.87	0.1	140	16.03	2.0	0	
3660	6729	422	-704	15.76	0.00	1.87	0.2	86	14.66	2.0	0	IC3963
3664	6806	426	24	14.70	0.00	0.00	0.0	0	14.19	1.0	0	NGC4864
3707	7220	472	255	17.76	15.96	1.82	0.4	116	16.56	2.0	0	
3706	6892	472	-371	17.61	0.00	1.85	0.1	167	16.44	1.0	0	
3730	7053	492	-670	15.27	0.00	1.94	0.1	26	14.16	1.0	0	IC3959
3794	6960	546	-40	17.37	0.00	1.98	0.1	101	16.12	1.0	0	
3896	7378	646	-491	15.13	0.00	1.75	0.0	0	14.18	5.0	2	IC3949
4230	7198	992	162	15.19	0.00	1.87	0.1	86	14.03	1.0	0	

Table 2: Subgroup 2.

GMP	VEL	X	Y	B	R	B-R	Ell	The	V	Type	Class	Ident
2541	7494	-722	-168	15.44	0.00	1.98	0.0	0	14.29	1.0	0	NGC4906
2559	7627	97	-695	15.44	0.00	0.00	0.6	152	14.83	6.5	0	IC4040
2551	7537	-709	158	16.85	0.00	2.99	0.3	78	15.36	2.1	1	
2651	7679	-571	6	16.19	0.00	1.85	0.3	101	15.07	2.0	0	
2721	7579	-493	-1249	17.50	15.65	1.82	0.4	179	16.33	0.0	0	
2861	7493	-367	378	16.26	0.00	1.85	0.2	134	15.02	2.0	0	
2914	7560	-313	680	17.18	15.40	1.81	0.2	117	15.89	0.0	0	
3084	7566	-132	568	16.43	0.00	1.82	0.1	39	15.30	1.0	0	
3113	7546	-87	461	17.82	16.08	1.81	0.1	147	16.65	0.0	0	
3254	7512	65	-8	16.57	0.00	1.84	0.4	55	15.87	2.0	2	
3486	7604	263	-130	17.73	15.79	1.82	0.1	136	16.67	1.0	0	
3487	7601	263	-9	16.63	0.00	1.88	0.4	67	15.80	2.0	0	
3640	7483	398	1011	17.13	16.23	0.00	0.4	95	16.41	0.0	0	
3761	7650	519	96	15.57	0.00	1.88	0.3	51	14.43	2.1	0	IC3955

Figure captions.

Figure 1. The redshift histogram of the main system (MS) of the core of Coma cluster. The revealed three galaxy subgroups are indicated (dashed lines), with the parameters given in Table 1.

Figure 2. The histogram of orientations of the galaxies in subgroup 1.

Table 3: Subgroup 3.

GMP	VEL	X	Y	B	R	B-R	Ell	The	V	Type	Class	Ident
2921	6497	-304	22	12.62	0.00	1.91	0.0	0	11.78	1.0	0	NGC4889
2252	5979	-1114	-548	16.10	0.00	1.85	0.3	56	15.08	1.0	0	
2516	6255	-762	3	15.34	0.00	1.86	0.0	0	14.21	2.5	0	IC4042
2805	6141	-422	337	16.57	0.00	1.78	0.4	73	15.47	2.0	0	
2945	6191	-278	-703	16.15	0.00	1.77	0.6	148	15.02	2.0	0	
2960	5922	-267	194	16.78	0.00	1.74	0.4	159	15.79	2.0	0	
3205	6200	14	-371	17.61	15.76	1.83	0.3	138	16.38	0.0	0	
3313	6210	111	-521	17.53	0.0	1.83	0.1	151	0.00	0.0	0	
3367	5848	166	47	15.15	0.00	1.91	0.3	108	14.42	2.0	0	NGC4873
3484	6082	262	9	16.26	0.00	1.81	0.4	50	15.49	2.0	0	
3493	6008	270	-833	16.50	0.00	1.94	0.5	9	15.22	2.0	0	
3879	5967	630	-1352	16.31	0.00	1.86	0.3	101	15.08	2.0	0	
3972	6018	721	410	16.52	0.00	1.87	0.6	167	15.29	2.0	0	
3997	5983	751	-575	15.28	0.00	1.95	0.0	0	14.15	2.0	0	IC3946
4083	6202	856	-516	17.82	15.84	1.91	0.4	79	16.44	2.0	0	
4103	5978	878	-59	17.74	15.96	1.76	0.6	126	16.21	0.0	0	
4315	5994	1104	-6	15.39	0.00	1.87	0.0	0	14.20	1.5	0	NGC4850

Table 4: Parameters of the Coma core main system (MS) and subgroups (1s, 2s, 3s): N denotes the total number of galaxies in the initial sample (T) and in each system; m the median velocity; σ, s, c , the standard deviation, 3rd and 4th moment of redshift distribution, respectively.

Coma core	T ($< 18m$)	MS	1s	2s	3s
N	188	174	34	14	17
m		6953	6892	7563	6013
σ		949	206	60	122
s		-0.2	0.4	0.4	0.1
c		-0.86	-1.1	-1.0	-1.4